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Standardized Emission Quantification and Control of Costs for Environmental Measures

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Abstract

Laser welding and soldering are important industrial joining processes. As is known, LGACs (Laser Generated Air Contaminants) cause costs for environmental measures during production of complex metallic components (steel, aluminium, magnesium, alloys). The hazardous potential of such processes has been assessed by analyzing the specific emissions with respect to relevant threshold limit values (TLVs). Avoiding and controlling emissions caused by laser processing of metals or metal composites is an important task. Using the experimental results, the planning of appropriate exhaust systems for laser processing is facilitated significantly. The costs quantified for environmental measures account for significant percentages of the total manufacturing costs.

Keywords: environmental protection; laser joining; metals; characteristic values of emissions; costs

1. Motivation and State of the Art

In highly automated laser welding and soldering processes, the potential for further reduction of production costs is very low. However, resulting indirect production costs, e.g. for the disposal of process by-products, offer further opportunities for savings. This is especially relevant for small and medium enterprises (SMEs), such as laser contract manufacturers and suppliers, which are exposed to a high cost pressure. In order to minimize investment and operating costs, the ventilation systems are planned specifically for each application in order to avoid costly over-sizing [1]. A cost-effective planning is only possible if the specific emissions for every type of joining procedure are known. Typically, a filter system is integrated into the process chain to capture both the emitted gases and fumes from the process zone. Databases of process emissions can be used in principle to predict emissions for an industrial process. However, the existing databases were established more than 10 years ago in most cases and thus are often not up-to-date.

In addition to the developments in laser technology, new trends occur in the field of semi-finished products, such as multi-metal material mixes. In the past, emission characterization has been carried out for laser ablation [2-4] and

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laser cutting [5], however, the old databases are not suited for predicting emissions of laser joining processes of different metallic materials (Figure 1). Due to the lack of up-to-date data, extensive experimental studies to quantify the gaseous and particulate emissions are required for the optimization of fume capturing and exhaust technology. In general, this is a very time-consuming procedure to be carried out for each specific laser joining process.

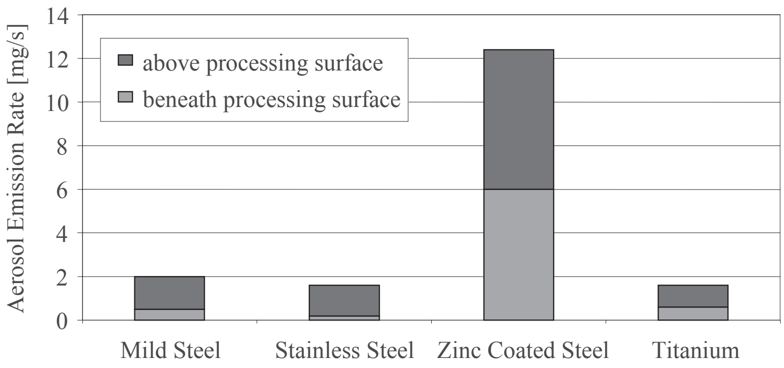

Figure 1. Aerosol emission rates during CO_2 laser welding of different metals (outdated), missing details.

The gaseous and particulate emissions of laser welding and soldering processes for sheet metal (mostly steel) have been investigated [6]. Various types of steel and surface treatments of the plates have been considered. The hazardous potential of these processes has been evaluated by analysis of specific emissions with respect to relevant threshold limit values (TLVs). The processes have been classified according to the measures required by German environmental legislation ("TA Luft" [7]). Finally, the costs of the emission-capturing technology (investment and operation) have been regarded in relation to the total production costs.

2. Measurement Setup and Procedure

The assembling of the emission line as well as the sampling and the analyses were carried out at different industrial facilities. For this purpose, an approved setup (Figure 2) was build up and calibrated.

After capturing the emissions of the joining process, the exhaust air, contaminated with fumes, was guided through the inlet pipe into a metering box in which the sampling was performed regarding gaseous and particulate emissions. For this purpose, a special testing compartment was integrated into the metering box and exhaust system, in which the sampling of several partial flows took place. The gas flows were piped to online sensors and discontinuous sampling media (e.g. glass fiber filters, DNPH solutions). After passing the metering box, the exhaust air was pumped through an outlet pipe into the ventilation and air cleaning system. The sampling was adjusted to the duration of the joining processes.

The experiments regarding the variation of relevant laser and process parameters and of weld-joint shapes were followed by the chemical analysis of the emission samples taken. The results of the analyses were rated, taking into account environmental and cost-related aspects.

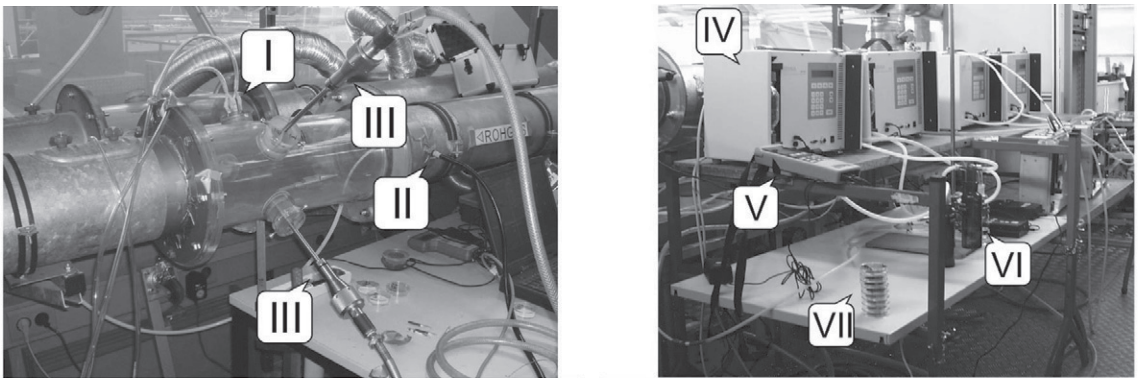

Figure 2. Experimental setup: applied sampling system, including metering box (left, I: sampling tubes, II: particle size distribution probe, III: sampling filter heads), and measurement setup (right, IV: air pump, V: analyzer (T, p, rH),
VI: DNPH dilution, VII: air sampling filters).

The setup of the emission line followed the German guideline VDI 2066 [8] to ensure a well-defined mixture and homogeneous distribution of the gases and particulate matter inside the metering box. It is important to generate a turbulent flow (Figure 3), because of the size of the sampling probes, which are much smaller than the diameter of the pipe. In this way, the flow rates and the partial flows can be regarded as constant inside the pipe, also with respect to the contained particles.

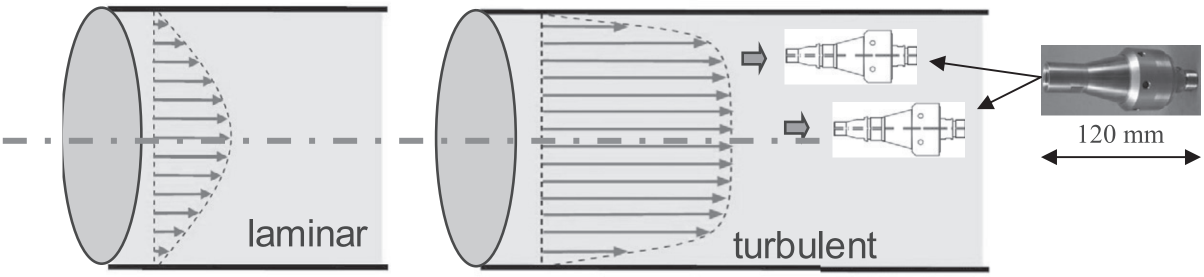

Figure 3. Left: Difference between laminar and turbulent flow in a pipe during dust sampling.
Right: probes for the sampling of the total dust at 2 different positions inside the pipe.

The mathematical discrimination between a laminar and a turbulent flow is given by the dimensionless Reynolds number. Thus, the turbulence inside a pipe starts at a certain threshold velocity. The appropriate Reynolds number depends on the pipe diameter, the gas viscosity, the flow velocity and is given as $Re_{crit} \sim 2320$ [9].

A further important boundary condition of the emission measurements is that the sampling of the particulate emissions has to be isokinetic according to [8]. Isokinetic means that all joining experiments have to be performed under well-defined air-flow conditions with equal velocities within the pipe and at the inlet of the sampling nozzles. In general, pipe and sampling probes are pumped off separately. Consequently, isokinetic conditions can be achieved by thoroughly adapting the nozzle diameter and the pumping power, dependent on the filter load.

Pressure, temperature and humidity were measured online during sampling to normalize the measured values afterwards, i.e. to calculate the effective standard volume. Gases and particulate emissions were investigated in the air flow simultaneously.

A detailed description of the experimental setup for sampling of gaseous and particulate emissions during laser material processing is given in [10].

2.1. Gaseous emissions

The carbon monoxide concentration in the air flow was measured online for all material combinations during the joining process. While processing metals with organic coatings, the gaseous total hydrocarbon concentration was also measured using a Flame Ionization Detector (FID). For improved analysis of the organic fraction, partial flows were piped through the absorption sampling tubes. These samples were analyzed by differentiating non-polar and polar hydrocarbons by GC-MS (Gas Chromatograph - Mass Spectrometer) as well as aldehydes and ketones using HPLC (High Performance Liquid Chromatography). The GC-MS samples were evaluated in terms of the most important components benzene, toluene, ethylbenzene and xylene. In addition, the GC-MS chromatogram was analyzed qualitatively by assigning the retention times, taking into account the typical peak intensities in the mass spectra of contemplable components.

2.2. Particulate Emissions

The particle size distributions of the fume emissions were measured online with an electric 12-stage low-pressure cascade impactor (ELPI) of Dekati Inc. (Tampere, Finland) [11]. The total amount and the chemical composition of solid and liquid particulate emissions (aerosols) in the air flow were determined in a discontinuously: The aerosols were accumulated in sampling filters. After defined time intervals, the total amount of aerosols - including inorganic and organic components - was determined gravimetrically.

The chemical composition of the particulate emissions with respect to inorganic elements was determined using SEM-EDX (Scanning Electron Microscope - Energy Dispersive X-ray spectroscopy) analysis. The SEM-EDX analyses displayed the percentages of single inorganic compounds in relation to all other compounds in the sample, but not its absolute concentration in the air flow. Quantitative chemical analyses were only performed if any dangerous inorganic compound was found in the SEM-EDX analyses (e.g. Cr during processing of stainless steel). In addition, quantitative chemical analyses on hazardous and volatile organic compounds were carried out (set of 16 PAHs (Polycyclic Aromatic Hydrocarbons), US-EPA (U.S. Environmental Protection Agency)).

In due consideration of

- the air flow volume in the exhaust system (depending on process),
- the partial gas flow through the sampling filters and online measurement systems, respectively, as well as
- the concentration of the particulate emission components,

characteristic emission values, including emitted mass per time [mg s^{-1}], were calculated. As an alternative, the amount of emissions was evaluated as mass per seam length [mg m^{-1}].

2.3. Experiments performed

For various laser joining processes (robots, remote systems), emission measurements have been carried out. In total, measurements have been performed with 12 material combinations and 3 joining variants (soldering, deep penetration welding, heat conduction welding, see Table 1). Different steel types have been investigated, including typical industrial surface treatments (pure, oiled, with residues of cold cleaning solvent, PTFE-coated and zinc-galvanized).

Table 1. Sample description and joining parameters (dp: deep penetration welding, hc: heat conduction welding, sd: soldering)

<table>
<tr><th>no.</th><th>materials</th><th>thickness [mm]</th><th>coating / treatment</th><th>laser type / output power</th><th>focal length [mm]</th><th>feed rate [mm s^{-1}]</th><th>spot size / weld seam [mm]</th><th>joining process variant</th></tr>
<tr><td>1</td><td>a: electrical sheet, b: mild steel</td><td>a: 0.1, b: 1.5</td><td>a: polymer coating</td><td>CO_2, 0.5 kW (cw)</td><td rowspan="4">200</td><td rowspan="4">17</td><td rowspan="4">0.15</td><td rowspan="4">dp</td></tr>
<tr><td>2</td><td>a: baking tray, b: mild steel</td><td>a: 0.5, b: 1.5</td><td>a: PTFE coating</td><td>CO_2, 0.75 kW (cw)</td></tr>
<tr><td>3</td><td>a+b: mild steel</td><td rowspan="2">a+b: 1.5</td><td>cold cleaner</td><td rowspan="2">CO_2, 1.0 kW (cw)</td></tr>
<tr><td>4</td><td>a+b: mild steel</td><td>forming oil</td></tr>
<tr><td>5</td><td>a+b: stainless steel 1.4404</td><td>a: 3.0, b: 5.0</td><td>none</td><td>Nd:YAG, 3.0 kW (cw)</td><td>200</td><td>58</td><td>0.2</td><td>dp</td></tr>
<tr><td>6</td><td>a+b: stainless steel 1.4301</td><td>a: 2.0, b: 3.0</td><td>none</td><td>CO_2, 3.4 kW (pulse max.)</td><td rowspan="2">200</td><td rowspan="2">5</td><td>1.2</td><td>dp</td></tr>
<tr><td>7</td><td>a+b: brass</td><td>a+b: 1.5</td><td>none</td><td>CO_2, 1.7 kW (pulse max.)</td><td>1.5</td><td>hc</td></tr>
<tr><td>8</td><td>a: DC 05/06, b: HLAD340</td><td>a: 0.7, b: 1.5</td><td>a+b: zinc-coated</td><td rowspan="4">Nd:YAG, 4.0 kW (cw)</td><td rowspan="4">200</td><td>60</td><td rowspan="4">1.5 – 2.0</td><td rowspan="4">hc</td></tr>
<tr><td>9</td><td>a: HLAD340
b: HLAD380 (Z 100 MB)</td><td>a: 1.5, b: 2.5</td><td>a+b: zinc-coated</td><td>30</td></tr>
<tr><td>10</td><td>a: DC06, b+c: HLAD340</td><td>a: 0.7, b+c: 1.5</td><td>a+b+c: zinc-coated</td><td>32</td></tr>
<tr><td>11</td><td>a: DC06, b: Usibor,
c: HLAD340</td><td>a: 0.7, b: 2.0
c: 1.5</td><td>a+c: zinc-coated</td><td>27</td></tr>
<tr><td>12</td><td>a+b: DC06 ZE 50/50</td><td>a+b: 0.75</td><td>a+b: zinc-coated</td><td>Nd:YAG, 2.7 kW (cw)</td><td>165</td><td>38</td><td>3.2 – 3.4</td><td>sd</td></tr>
</table>

If necessary, e.g. in case of processes with large particle amounts, the sampling was divided into several short periods to avoid filter overloading. Thus, the complete testing time depended strongly on the loading of the sample collection media. The timing was started at the beginning of the joining process, stopped at the end of the process and recorded manually with a stop watch.

For each process, the specific emission rates of airborne particulate and gaseous pollutants were determined within the exhaust system as described above. Depending on the location of the laser joining process, the stationary or the mobile testing setup with sampling instrumentation was used. Each experiment was repeated three times for statistical validation.

3. Evaluation of results

Table 2 displays the relevant emission values of all investigated joining processes according to the German regulations for exhaust emissions [7]. As the fraction of volatile organic and inorganic compounds in the aerosol is always below the corresponding TLV according to [7], it is not listed in Table 2. Only the characteristic values for total aerosol emission are given.

Table 2. Aerosol emission rates and concentrations measured in the exhaust air. Values that exceeding TLVs are marked red.

process no. acc. to Table 1	process (Table 1) / thickness [mm]	remarks	laser power [kW]	*total aerosol emission rate [g h^{-1}] (TLV = 200 g h^{-1})*	*total aerosol conc. [mg m^{-3}] (TLV = 150 mg m^{-3} at emission rate < 200 g h^{-1})*	*environmentale ffort category*
1	dp thickness 0.5 + 1.5	lap joint	0.5 (cw)	15.4	13	1
2	dp thickness 1.0 + 1.5		0.75 (cw)	9.6	8	1
3	dp thickness 1.5 + 1.5		1.0 (cw)	18.1	15	1
4				19.2	16	1
5	dp thickness 3,0 + 5,0	circular seam	3.0 (cw)	2.3	17	1
6	dp thickness 2.0 + 3.0	circular seam	3.4 (pulse max.)	1.4	6	1
7	hc thickness 1.5 + 1.5	longitudinal seam	1.0 (pulse max.)	3.1	16	1
8	hc thickness 0.7 + 1.5	cabin capturing off	4.0 (cw)	23.6	118	1
		cabin capturing on		20.0	100	
9	heat cond. welding thickness 1.5 + 2.5	cabin capturing off		33.2	*166*	2
		cabin capturing on		18.6	93	
10	hc thickn. 0.7 + 1.5 +1.5	cabin capturing off		25.5	128	1
		cabin capturing on		18.9	95	
11	hc thickn. 0.7 + 2.0 + 1.5	cabin capturing off		38.3	*191*	2
		cabin capturing on		23.0	115	
12	sd thickness 0.75	cabin capturing off	2.7 (cw)	11.8	59	1
		cabin capturing on		7.1	36	

Comparing the emissions measurements with the TLVs listed in [7], the laser processes can be categorised into the following emission categories, leading to different measures for the cleaning of exhaust air:

- Cat. 1: No filtering measures for the exhaust air are necessary since all emissions comply with the TLVs.
- Cat. 2: Particle filters according to the state-of-the-art are required if specific aerosol TLVs are exceeded.
- Cat. 3: Filtration of gases according to the state-of-the-art is mandatory if TLVs for specific gaseous components are exceeded.
- Cat. 4: Additional measures are required, because e.g. acidic gases are emitted from the process zone, which must be neutralized using the state-of-the-art techniques (usually not relevant for laser joining of metals).

Every laser process examined in this work is categorised into Cat. 1 or 2, because of the quality of its fume composition. Considering the related mass flows and particle concentrations the most processes are categorised into Cat. 1.

It has to be noted that the hazardous potential of nanoparticles has not been taken into account in the frame of the described classification. It cannot be excluded that the categorisation will change if the nanoparticulate character of joining process emissions is taken into account in future emission rules and environmental legislation.

Finally, the calculated characteristic emission values were valuated by comparing them with the guideline 'Technical Rules for Hazardous Substances' (TRGS 900 [12]), which lists relevant occupational exposure limits (OELs). Each joining process causing a certain extent of measurable emission was rated in terms of air purification into four categories. Consequently, the determined characteristic emission levels were correlated with the total costs (e.g. production costs of the laser process) and the relative costs for environmental measures.

4. Costs for environmental measures in relation to the overall process costs

As starting point of the assessment of financial aspects of the environmental measures, the overall costs of the investigated joining processes had been estimated by different involved industrial partners of the authors. Based on these data, the costs for installation and operation of efficient capturing and filtration technologies for exhaust air cleaning (costs for environmental measures) were calculated. Linear 5-year-depreciations of investments, operating costs, electrical consumption and maintenance costs were taken into account.

The costs for environmental measures are correlated to the emission category of the laser joining process. These costs increase significantly from Cat. 1 to Cat. 4. Hence, the ratio of costs for environmental measures and the overall costs is an adequate criterion for classifying the laser processes in terms of exhaust air cleaning:

- Level A: low costs ≤ 15 %
- Level B: 15 % < moderate costs < 30 %
- Level C: high costs ≥ 30 %

The cost levels were determined in cooperation with industrial partners. As shown in Table 3, the costs for air purification within all investigated joining processes and combinations of materials (Cat. 1 - 2) are below 15 % (Level A).

Table 3. Environmental costs in relation to the overall process costs

process no.	laser type	process	overall process costs	costs for environmental measures	percentage of overall costs
1	CO_2 (cw)	dp	75 €/h	10.75 €/h	14.3 %
2	CO_2 (cw)				
3	CO_2 (cw)				
4					
5	Nd:YAG (cw)	dp	90 €/h	4.70 €/h	5.0 %
6	CO_2 (pulsed)	dp	85 €/h	4.70 €/h	5.5 %
7	CO_2 (pulsed)	hc	60 €/h	4.70 €/h	7.8 %
8	Nd:YAG (cw)	hc	100 €/h	8.30 €/h	8.3 %
9					
10					
11					
12	Nd:YAG (cw)	sd	115 €/h	8.30 €/h	7.2 %

Joining processes with rating Cat. 3 and Cat. 4 will exceed the limit of cost level A for exhaust air purification (15 % of the overall costs). The reason is the necessity of complex additional cleaning and filtering methods in order to comply with environmental and occupational laws.

The results are available via the interactive internet database [13], which has been revised in the course of the work described here. This database will be expanded by further emission measurements.

5. Filter design and air-to-cloth ratio

The task of any filter system is to reliably purify a specified exhaust gas to comply with given limits for dust and other pollutants. Many parameter influence the filtering complexity: the carrier gas (usually ambient air), the particles and the filter medium properties, the operation mode, as well as the filter design. The optimum filter design and its size, which largely determines the cost structure of the whole precaution system, cannot be calculated accurately without reliable emission data. Therefore, the filter design is determined on the basis of empirical data and test series. On the one hand, cost optimization depends on the efficiency and power of the exhaust purification system, which is able to ensure effective capturing and cleaning. On the other hand, the optimal relation between interdependent design parameters, air-to-cloth ratio, and pressure loss of the filter significantly affect the overall cost structure. The air-to-cloth ratio [m^3 m^{-2} h^{-1}] defines the flow through a filter surface in a given time. The air-to-cloth ratio is dependent on various factors and affects the performance of a filtering system. A large air-to-cloth ratio (~ 120 m^3 m^{-2} h^{-1}) [14] and a minor pressure drop caused by the filter (< 2500 Pa for particles < 0.5 µm) [15] should be the main objective of the filter design.

Within this work, the air-to-cloth ratio was considered in detail. The technical data of the exhaust systems located at the project partners manufacturing lines are presented in Table 4.

Table 4. Air-to-cloth ratios of the used filter systems

Company / process no.	manufacturer's design flow rate of the fan [m^3 h^{-1}]	permitted/valid air-to-cloth ratio [m^3 m^{-2} h^{-1})]	required filter area [m²]	actual filter area [m²]
Company A / (1)-(4)	2,200	120	18	30
Company B / (5)	500		4.5	40-80
Company C / (6)-(7)	6,000		50	100
Company D / (8)-(12)	3,500		30	50

Only in one case regarded here, the filter of the exhaust air system is oversized. The other purification systems run with optimized filter dimensions and hence are economically. This shows, that in industrial routine adequate filtering methods are available and in use.

The prime parameters for the economic efficiency of a filter system are in detail: low investment costs, high air-to-cloth ratio (leading to the best saturation condition of the total filter area), low fan energy costs with respect to minor pressure losses (here, the data for systems of different suppliers and operators vary from 20 to 80 % of the total filter operating costs), low costs for compressed air, high endurance, and high availability [16].

6. Summary and Discussion

In this work, different laser joining processes (welding and soldering) of metallic materials have been analyzed with regard to their gaseous and particulate emissions, which are potentially hazardous. After characterizing the process exhaust air by means of different experimental techniques according to the German environmental legislation [7], the determined emission rates have been correlated to the specific costs for environmental measures, leading to characteristic emission numbers such as costs per processing time [€ h^{-1}] or costs per seam length [€ m^{-1}]. Based on these results, it can be concluded that there is a strong dependence of the resulting costs for environmental measures (air capturing, cleaning and disposal) on the types of emission products and on the emission rates. The costs for environmental measures have been correlated to the total process costs which have been determined by means of detailed cost analyses in cooperation with the industrial partners involved.

For a systematic classification of the laser joining processes, 4 categories have been defined in order to rank the expenses with regard to measures for environmental protection in the field of laser soldering and welding of metals. These categories are directly related to the compliance of threshold limit values for particulate and gaseous emissions according to [7]. All investigated laser joining processes (see Table 1) are assigned to the lower categories 1-2. Considering the associated mass flows and concentrations, most of the processes are categorized to 1. Additionally, 3 cost levels have been defined, characterizing the laser processes on the basis of the costs for required measures for environmental precaution. The evaluation shows that all investigated processes are assigned to the lowest cost level of environmental precaution (< 15 %). Often, the costs of exhaust air purification are even smaller than 8 % of the total process costs, which is comparable to laser cutting of polymers with a typical cost fraction of about 10 % for handling and filtration of the exhaust air [5]. This clearly shows that an adequate dimensioning of the environmental measures, which are related to industrial laser joining, is possible in an economic way.

The aforementioned interactive database "Laser Safety" [13] has been revised. It provides details of laser process emissions and is available in the internet since several years. For example, the achieved information concerning the costs for environmental measures and the cost levels of different laser joining processes are available now. Using the database, planning and selection of suitable exhaust systems for laser welding and soldering are simplified. Thus, the database supports both SMEs (e.g. automotive suppliers) and large concerns, because the experimental efforts for studies on the optimization of the exhaust system for the laser application which is regarded here can be scaled down.

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